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ACCURATE DETERMINATION OF THE COMPLEX PERMITTIVITY OF BIOLOGICAL TISSUE AT 90 GHz, 70 GHz, AND OVER A BROAD BAND AROUND 35 GHz

Rodney J. Sheppard, Ph.D.

Physics Department
King's College London
Strand, London WC2R 2LS, UK

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USAF SCHOOL OF AEROSPACE MEDICINE
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European Office of Aerospace Research
and Development (LSB)
223-231 Old Marylebone Road
London NW1 5TH, UK

NOTICES

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The Office of Public Affairs has reviewed this report, and it is releasable to the National Technical Information Service, where it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for publication.

Johnathan L. Kiel

JOHNATHAN L. KIEL, Ph.D.
Project Scientist

David N. Erwin

DAVID N. ERWIN, Ph.D.
Supervisor

George Schwender MD

GEORGE E. SCHWENDER, Colonel, USAF, MC, CFS
Commander

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The design of a new experimental system to measure the complex permittivity of liquids and solid tissues at 90 GHz is considered. A circuit diagram is presented, and an experimental cell (sample holder) of circular cross section is described. A numerical method which would enable alternative designs of cell to be considered, is presented.

A broad-band system to measure complex permittivity around 35 GHz has been designed, and we confidently believe this equipment can be set up to cover the full bandwidth of 26 to 40 GHz.

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ACCURATE DETERMINATION OF THE COMPLEX PERMITTIVITY OF BIOLOGICAL TISSUE AT 90 GHz, 70 GHz, AND OVER A BROAD BAND AROUND 35 GHz

1. INTRODUCTION

During 1984 to 1986 a research program was undertaken for the U.S. Air Force (USAF) to set up precision waveguide apparatus to measure the complex permittivity of solid tissues and liquids of biological interest at a spot frequency of 35 GHz. The details of this work have been set out in a final scientific report (1) and also published journal articles (2, 3).

The prime objectives for this program are to extend the measurement capability to 70 and 90 GHz and to broaden the operating frequency band of the system at 35 GHz. The work is being divided into two separate but linked projects: one concerning the 90-GHz apparatus;and the other,the 35/70-GHz systems.

Unfortunately there was some delay in the authorization of the grants and the first financial payment so that it was not possible to start the work on 15th September 1987. However the 90-GHz project started in October 1987 and the 35/70-GHz work in May 1988. We request that this report be viewed as representing 1.25 years work at 90 GHz and rather less than 1 year's work at 35/70 GHz.

2. BACKGROUND

The need for accurate permittivity data on biological systems and in particular tissues was set out in the original grant application and will not be repeated here.

In general, permittivity measurements on such systems are difficult at millimeter wavelengths since the waveguide dimensions are small, the wavelength and hence distances to be measured are small,and any aqueous systems have a very high microwave absorption. The values to be expected for data can be predicted from the familiar Debye Equation, namely

$$\epsilon = \epsilon_s + \frac{\epsilon_s - \epsilon_\infty}{1 + f/f_r}$$

where ϵ_s and ϵ_∞ are the static and high frequency permittivities, f is the frequency of the applied microwaves and f_r the relaxation frequency. With literature values for the data (see Reference 3), Table 1 compares data for water and tissues at 35 GHz with that to be expected at 90 GHz.Data at lower frequencies are being used to extrapolate the dielectric properties at 90 GHz. The data, when measured, at 90 GHz will likely be similar; and it is an important part of the work to investigate whether this is so. If significant differences should be found from the measured and the predicted data of Table 1, then this finding would have significant consequences concerning microwave hazards.

TABLE 1. COMPARISON OF QUARTER WAVELENGTHS OF VARIOUS SAMPLES AT 35 AND 90 GHz

Sample	Temp	Frequency (GHz)	E'	E"	Alpha (dB mm-1)	Alpha/Beta (dB)	WL/4 (mm)	CWL/4 (mm)
Water	30	90	9.4	16.1	35.7	5.1	.23	.27
Water	30	35	25.1	31.4	17.6	4.2	.38	
Water	20	90	8.2	13.4	31.8	4.9	.24	.29
Water	20	35	19.6	28.7	17.6	4.6	.41	
Grey	37	90	8.1	13.8	32.6	5.0	.24	.30
Grey	37	35	21.3	20.0	12.7	3.5	.43	
Grey	20	90	9.5	7.7	19.0	3.1	.26	.27
Grey	20	35	17.0	18.6	13.0	3.9	.47	
Fat	20	90	3.4	.92	4.1	1.2	.45	.46
Fat	20	35	3.4	1.3	2.3	1.8	1.2	

NB: WL/4 and CWL/4 is the quarter wavelength of sample in rectangular wavelength and circular waveguide respectively.

The expected loss value (alpha) at 90 GHz is about twice as large as that at 35 GHz and the quarter-wavelength thickness, to which the sample thickness is directly related, is about half the 35-GHz value (Table 1). Note that the wavelengths and losses between 35 and 90 GHz are not directly proportional to the frequency (wavelength) since to the permittivity ϵ is varying. This difference is mainly due to the water both free and bound within the tissues which will disperse over the region.

3. SPECIAL PROBLEMS AND PROGRAM PLAN

At 90 GHz, the main problems are the small size of the waveguide and the high loss of aqueous systems. The waveguide used will be W-band whose internal dimensions are only 2.54 x 1.27 mm whilst as can be seen from Table 1, the electric field is expected to decay in water by about 30 dB per millimeter. Thus, it would not be possible to build a system at 90 GHz, identical, apart from guide size, to that already in use at 35 GHz and to automatically expect good data to be obtained. In particular, the design of the experimental cell (sample holder) will have to be completely reassessed. It is also more difficult to obtain relatively powerful and stable microwave sources.

At 35 GHz the main objective is to broaden the bandwidth of the system without compromising accuracy. Again, the main problems are experimental cell design and sources whilst intrinsically narrow-band items such as ferrite isolators also need careful consideration.

The 70-GHz system is expected to be the easiest to construct. In particular, this system it will operate at a single frequency and the problems of source and cell design should not be as difficult as those at 90 GHz.

Presently all research effort will be concentrated on the 35-and 90-GHz systems. Then, once the 90-GHz is operational it should be relatively straightforward to set up the 70-GHz apparatus, basing it closely on the higher frequency system.

4. THE 90-GHz SYSTEM

4.1 The Experimental Cell - General Considerations

As set out in the preliminary report to this project (4) various types of experimental cells have been considered and are compared below.

(a) In-Guide Cell

This cell is the type of cell used for previous microwave permittivity measurements. The sample (liquid or solid) is placed in a specially constructed section of the waveguide being used. Although it would be possible to surround the sample with transparent windows and to make a transmission measurement, it is often preferable to terminate the sample with metal short circuit and to use a reflection technique. At frequencies up to 35 GHz, this type of cell is the method of choice since the field inside the sample is known and, in particular, it can be assumed that higher modes of propagation will not be present in a well designed and constructed cell. However, the concern at 90 GHz is whether a precision cell could be built in a waveguide whose internal dimensions are only 2.54 x 1.27mm with samples in the order of 0.33 mm thick.

(b) Cavity Cells

The use of a microwave cavity is well accepted for dielectric measurements. The sample is placed in the cavity and the change in the Q factor, which is a measure of the sharpness of the resonance, together with the frequency shift of the resonant peak, enables the complex permittivity to be calculated. However, for high loss substances only very small samples can be used if the system is to be sensitive. Such methods have not been favored since the small samples have to be placed accurately in a known position in the cavity and this limits the precision for high loss substances. Certainly at 90 GHz the problems encountered would be greater rather than smaller compared to lower frequencies.

(c) In-Vivo Methods

For these methods an applicator, consisting of an open-ended guide, is placed on the surface of a sample, and the complex permittivity is deduced from the reflected signal. The advantage, apart from being able to study living systems, is that no sample preparation is required. The disadvantage is that the electric field becomes a very complicated function of the sample and indeed no known exact solution exists to compute the complex permittivity from the observed data. However, approximate solutions have been obtained and some success has been achieved, particularly for coaxial line systems at lower frequencies (5).

(d) Modified In–Vivo and Overmoded Guides

It has been suggested (6) that a sample could be placed at the end of an open waveguide and a short circuit placed at the opposite side of the sample to reflect the signal back into the guide. Again, sample preparation is simpler than for in-guide systems and the method can be more sensitive than true *in–vivo* methods if a short circuit is placed a quarter wavelength from the end of the guide. It may be expected that the data analysis will be easier although an exact solution is still not possible.

An alternative is to use an overmoded waveguide (i.e., to construct a cell of larger dimensions than W-band). Unlike the *in–vivo* methods, the possible number of higher modes will be finite and small if the guide is not too oversize. However, the transition from the W-band system to the large experimental cell has to be carefully considered and although the data analysis is simpler than *in–vivo* method it is far from trivial and an exact solution is still not possible.

(e) Conclusions

We believe that an in-guide method is still the most likely to yield accurate data, even at 90 GHz. However, we and our engineering workshop were concerned as to whether sufficient precision could be obtained in a rectangular waveguide. Thus, we have decided to use W-band rectangular guide for most of the system but to have a transition to 90-GHz circular waveguide before the experimental cell and to construct the cell from circular guide since it is possible to achieve higher precision in a circular rather than rectangular system.

4.2 The 90-GHz Cell

The prime requirement is a circular pipe with a high precision internal bore. The tolerances required are beyond the limits of the workshop at King's College and the pipe has been manufactured for us by Flann Microwave Limited. The circular cell consists of a length of 5 cm diameter brass with a hole of internal diameter 2.39 mm having a tolerance of ±0.01 mm over a 40-mm length. The internal hole has to be plated to prevent biological samples reacting with the cell. At present the plating is being done in gold by the Physics Department at King's College.

However, if this approach is not successful then Flann would be able to provide a hole to the same tolerance in a block of silver.

Another possibility being investigated is for Precious Metal Depositors (U.K.) Limited to electroform silver or even platinum onto a steel mandrel, and this process could be done to a tolerance of ±0.1 μm.

Thus, we are confident that a circular cell of at least the required accuracy will be completed in the near future. As with previous cells a very rigid framework is required to hold the cell and ancillary waveguide components; this frame has been designed and is being constructed in the Physics Department Engineering Workshop at present.

A diagram of a cell suitable for liquid measurements is shown in Figure 1. The cell has a fixed dielectric plug of nylon at one end and a moving short circuit at the other end with the liquid contained between. The short circuit will be fixed to and moved by a block of Tufnol. The short circuit will have a clearance of 0.05 mm between itself and the cell walls whilst the Tufnol will have two grooves 0.1 mm in depth to enable the liquid to escape as the short circuit moves towards the nylon plug. This cell follows previous designs for liquids; the essential differences are that it is constructed from circular rather than rectangular pipe and very high tolerances are required.

As in previous systems a different cell is required for solid samples since clearly a moving short circuit displacing the sample would not be possible. The proposed cell is shown in Figure 2,and the sample will be loaded onto a dielectric window close to the open end of the cell. The window position will be such as to give a quarter-wavelength sample, and again the system will be built in a circular pipe. A steel shaft will then drive the short circuit onto the tissue sample as shown in Figure 2. However, a major problem is to decide when the short circuit has made contact with the sample, particularly with the softer tissues. Pressure sensors are presently being investigated to see whether any might provide a suitable way of terminating the short-circuit movement. Most commercial sensors tend to be designed for much higher pressures than required and not to have sufficient accuracy; however, investigations are continuing.

An alternative method we have devised and are investigating is to make use of the conductive nature of tissues. It is proposed to apply a low level direct current (D.C.) potential across the sample and short circuit and a conductive path will be detected when the short circuit contacts the tissue.

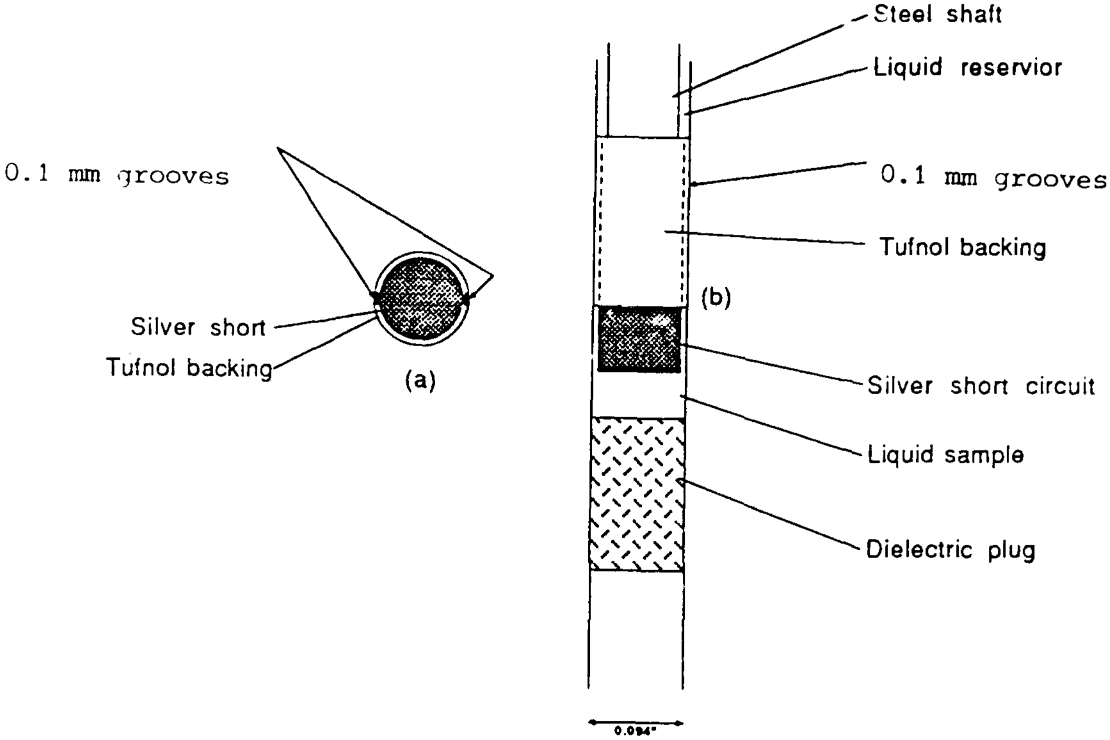

Figure 1. The circular waveguide liquid cell; (a) transverse cross-section, viewed from below, (b) longitudinal cross-section.

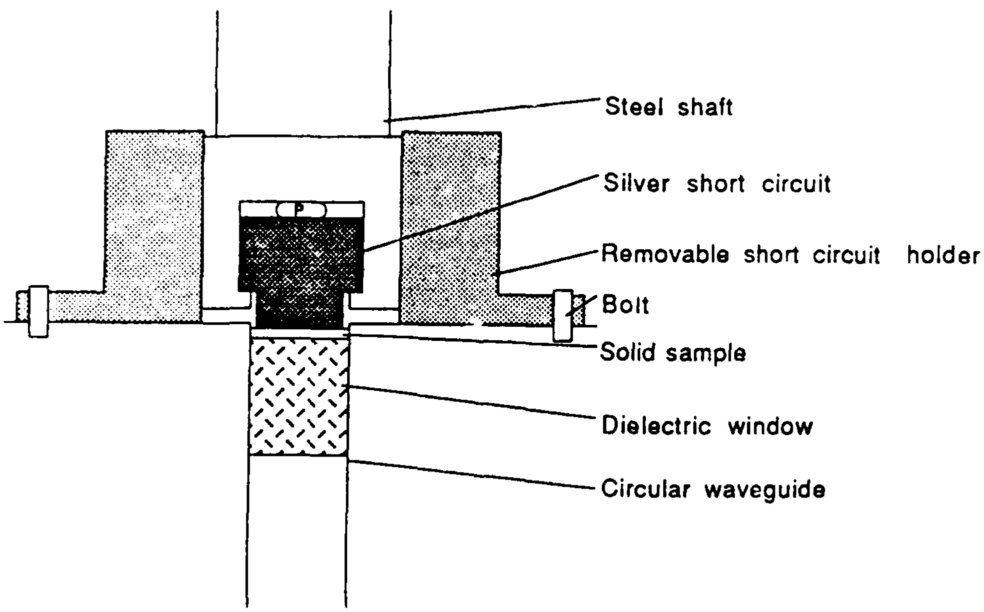

Figure 2. The circular waveguide solid cell. P Analog/Digital pressure sensor.

4.3 The 90-GHz System

The proposed waveguide circuit is shown in Figure 3 and is based on that used previously at 35 GHz. It is not proposed to list all the apparatus; however, items of special interest are described next.

The microwave source has been specially developed for us by the American waveguide component manufacturer, Millitech Corporation. This source, model GDM-26-HI, is shown in Figure 4 and consists of a dual-diode oscillator, with micrometer tuners for each diode and also a back plane tuner. The system is able to provide 110 mW of stable microwave power and it is believed that this unit represents a commercial world first as regards power and stability at 90 GHz. The source has a mechanical tuning range of ±0.25 GHz and an electrical bias tuning range of ±100 MHz. This system has a heater to keep the temperature constant and the unit will be operated around 40 °C (104°F). The source has been delivered and on test achieved a free running stability of ± 5 MHz after only 10 min warm-up period. Free running stability is important since although we have an (EIP) frequency counter, provided for the previous 35-GHz project and able to measure and stabilize to ± 1 Hz, this unit will only be able to check frequencies at 90 GHz since it will be in almost continuous use for the broad-band 35-GHz system.

We were pleased with the initial performance of the oscillator. Sadly a problem developed and at the time of writing (January 1989) the unit is back in the United States for investigation and repair. However, since the unit is new and at the limit of technology, we believe some initial problems are to be expected.

The microwaves will be modulated with a (PIN) diode switch (Millitech model PSP-100) and the modulation source to drive this switch has been designed and built in the electronics workshop of King's College. The input to the unit is via an RS423 interface so that it can be directly controlled from an on-line computer.

A motorized waveguide attenuator (Millitech model MWA-10-G) will be used to calibrate the detector; this attenuator and its drive unit, together with the PIN diode and its modulator source are shown in Figure 5. The detector is from Millitech, model DXP-10, and has a linearity of 2 to 3% over a 50-dB range.

As seen, many of the waveguide components are from Milltech Corporation. Although we had not dealt with this company before we have been impressed by their ability to respond to our specialized needs. The more mundane components such as bends and twists are from our usual supplier - Alpha Limited; however, one major item purchased from Alpha is the slotted line (model 740 W).

Apart from the small dimensions of the waveguide and cell the other major problem concerns the small sample thickness (~ 0.33 mm) and the corresponding small distances to be measured.

For sample preparation, we have experimented with Vibratome equipment to produce very thin slices of tissue sample and success has been achieved.

Concerning measuring small distances we have purchased from Ealing Electro Optics Limited an IEEE controlled stepper unit. This unit is able to step 0.1 μm with a

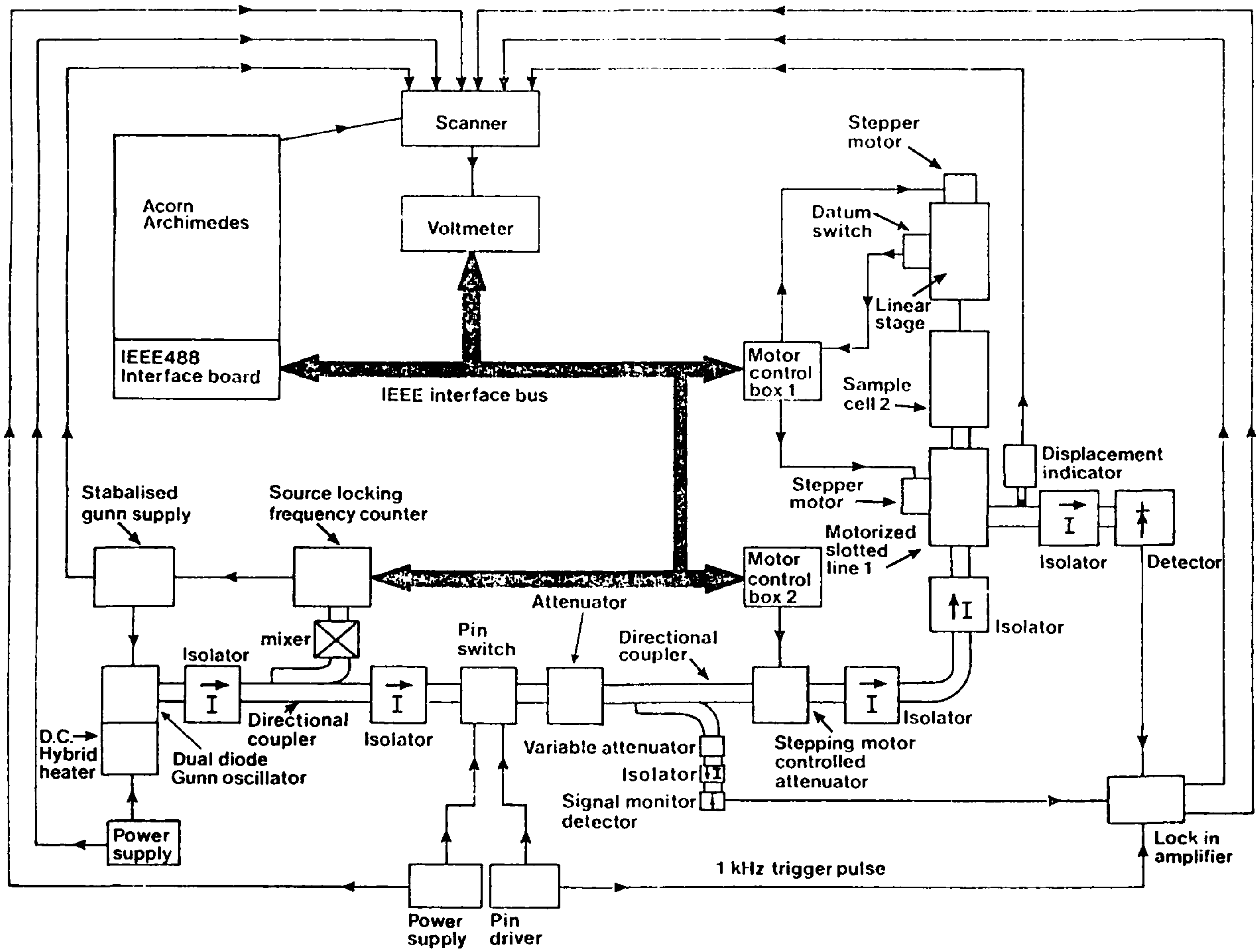

Figure 3. A schematic diagram of the 90-GHz apparatus.

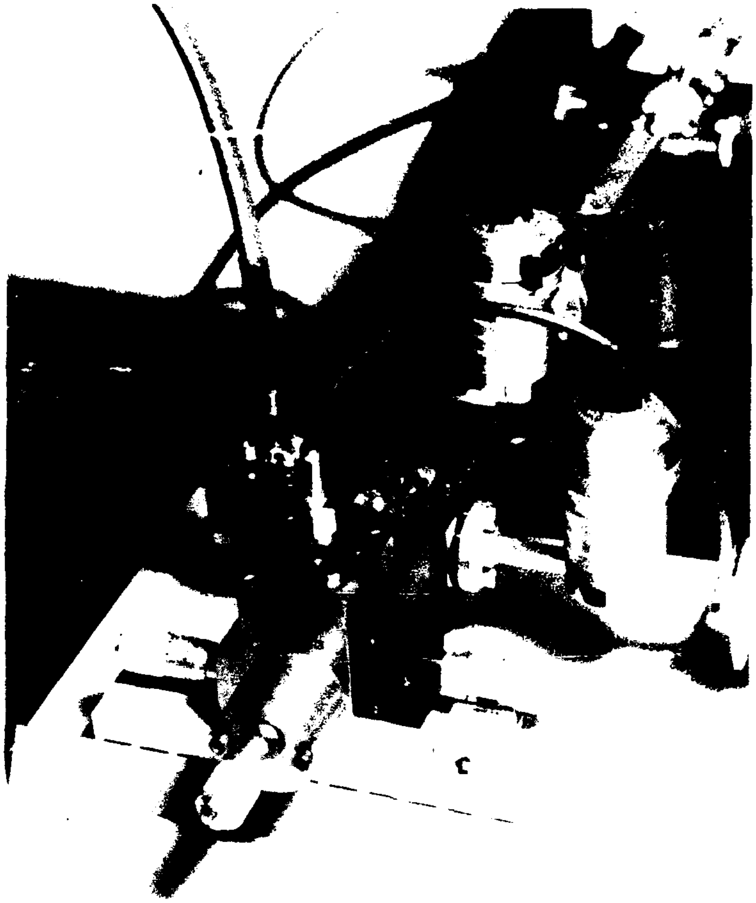

Figure 4. *The 90-GHz oscillator.*

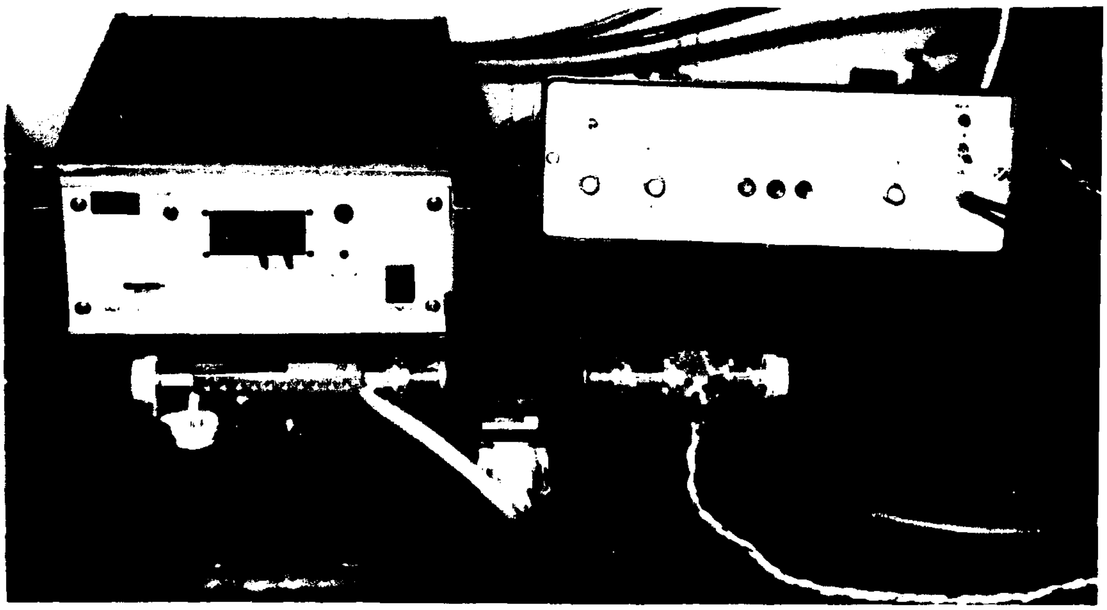

Figure 5. The PIN Diode, the motorized attenuator, and their driving units.

total accuracy of ±1 μm and it will be used to automate the slotted line. The stepper unit and slotted line are shown in Figure 6. Since the absolute accuracy of this unit is of such vital importance to the project, we checked the stepping unit against various digital measuring devices existing in the laboratory. We were concerned to find discrepancies and returned the stepping equipment to Ealing for checking. They agreed that the unit was not within specification, and at present a new unit is being manufactured.

For measuring sample thickness we are experimenting with a "Mu-checking" cartridge head from Mitutoyo (Model 519-334). This unit gives an output from -1 to +1 VDC over a 1 mm travel with a resolution of 1 part in about 10^5. We intend to calibrate the system against the Ealing stepping unit to provide a second but relatively inexpensive distance measuring system.

Accurate temperature control of the sample is always necessary during measurement and a Temperature Circulator (model FH16-D) has been purchased from Grant Instruments. The system has a temperature setting accuracy of ±0.1 °C (±0.18°F) but a temperature stability and accuracy (with an external thermometer) of ±0.007 °C (+0.013°F). The unit has an external temperature sensor so that the temperature can be controlled at the sample rather than in the external water bath.

The situation as of January 1989 is that all the 90-GHz equipment has been delivered and tested. The cells are being constructed in our engineering workshop and as soon as the oscillator is returned from Millitech test measurements will begin.

5. THE COMPUTER SYSTEM

It is convenient to consider computer aspects of the project at this stage since the same microcomputers are being used for the 90-GHz and broad-band 35-GHz systems to ensure compatibility across the equipment. For previous systems Research Machines 380Z microcomputers have been used. These computers have been very reliable and useful machines, but their age is such that a new generation of computer was required for this work.

The system chosen is the Acorn Archimedes, a 32 bit RISC machine with 1 Mbyte of RAM which can be upgraded to 4 Mbytes; there is also a 20-Mbyte hard disc. The machine will be able to interface with and thus control various microwave components via the standard IEEE-488 Bus.

The system was chosen as being reasonably priced, yet state of the art, which we believe will be capable of acquiring and analyzing the data. So far, existing least-squares curve-fitting routines have been modified and updated to run on the Archimedes. Much work has been done concerning the optimisation of sample thickness/maximum sensitivity, particularly for the broad-band 35-GHz system and this work is described in the following section.

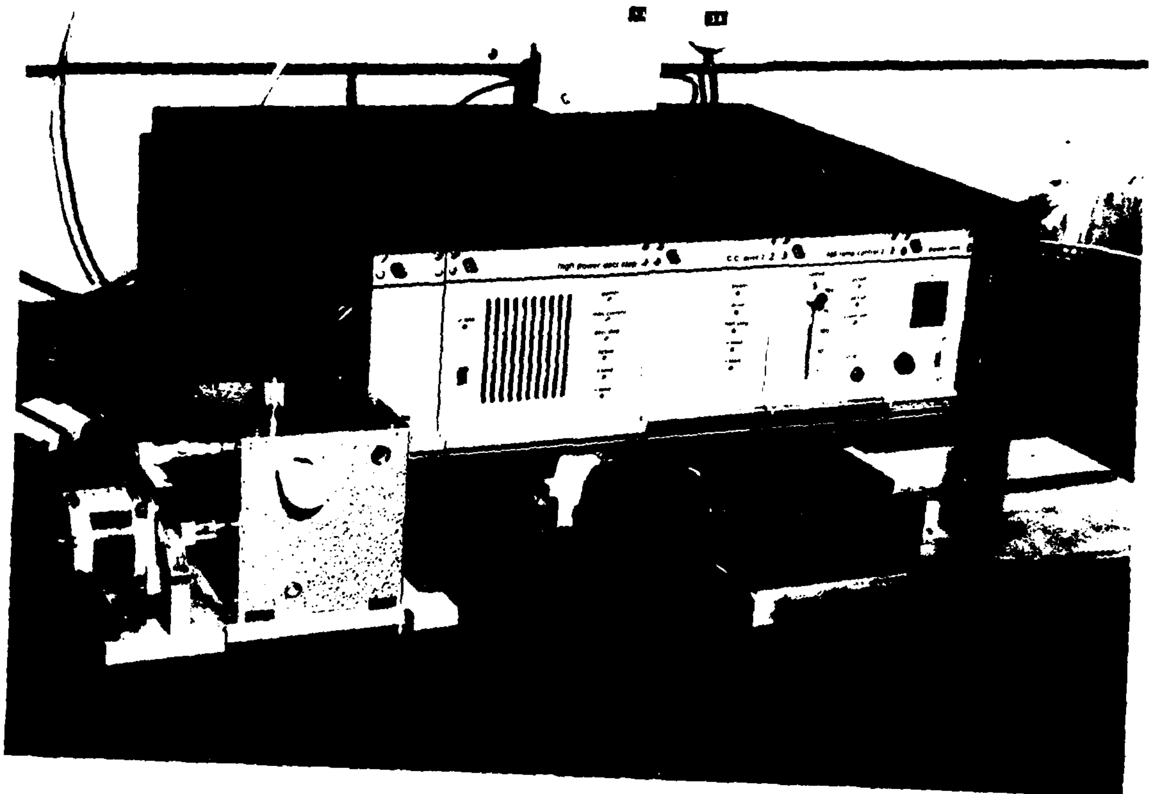

Figure 6. Stepper unit and slotted line.

6. COMPUTER MODELING

6.1 Introduction

At present we cannot be sure that the circular waveguide cell as described in the previous section will yield the accuracy required, and other designs are being considered. However, in these cases the data analysis is far more difficult, no exact solutions are known and numerical methods are used.

The original work was funded by the (British) Cancer Research Campaign, and the objective was to compute the electromagnetic (EM) field inside patients to optimize the deposition of energy during clinical hyperthermia. The computer software developed uses a technique known as a Time Domain Finite Difference Simulator (TDFDS) and is able to calculate the EM field inside 3-dimensional objects of complicated geometry. I realized that this technique could have applications beyond the field of Cancer Therapy and the present author has been involved in raising venture capital and forming a company to make the software available to industry. The areas of market interest include microwave heating, both domestic and industrial, the design of antenna and strip lines and areas of EM compatibility, particularly concerning EM pulses propagating through apertures into aircraft.

Concerning the present AFOSR project the software is being used to consider numerically the behavior of alternative 90-GHz experimental cells. The work is part of a wider project to enable tissues to be measured at waveguide frequencies using *in-vivo* methods. The project is being funded by King's College rather than AFOSR but those aspects which will assist the 90-GHz project are described next. This work is in addition to the work suggested in the grant application to AFOSR, and no charges are being incurred by the USAF.

6.2 The Finite Difference Time Domain Simulator

We do not propose here to give a full review of numerical methods for field computation. However, in brief, some methods reduce the problem to a matrix, which has to be inverted; or differential equations to be solved, but such techniques are not always suitable for complicated 3D systems. In particular, the matrices can become too large for inversion and the differential equations too complicated to solve when used with real systems.

The Finite Difference Time Domain Simulator (FDTDS) does not suffer from these limitations and has been found to work well on complicated 3D systems. Essentially a numerical model is built and an EM field is applied to it. In Figure 7 the EM field may be known at the plane of application (AB of Fig. 7) and will be zero to the right of this plane at the moment of switch on ($t = 0$). If, for example, the field is applied from a simple waveguide applicator at AB then it will be known analytically. If not, then the modelling can begin further back at the point of field excitation.

We believe that all EM phenomena can be described by the Maxwell Equations of EM radiation which can be written as

$$\nabla \wedge \boldsymbol{E} = - \ \boldsymbol{B} \qquad (1)$$

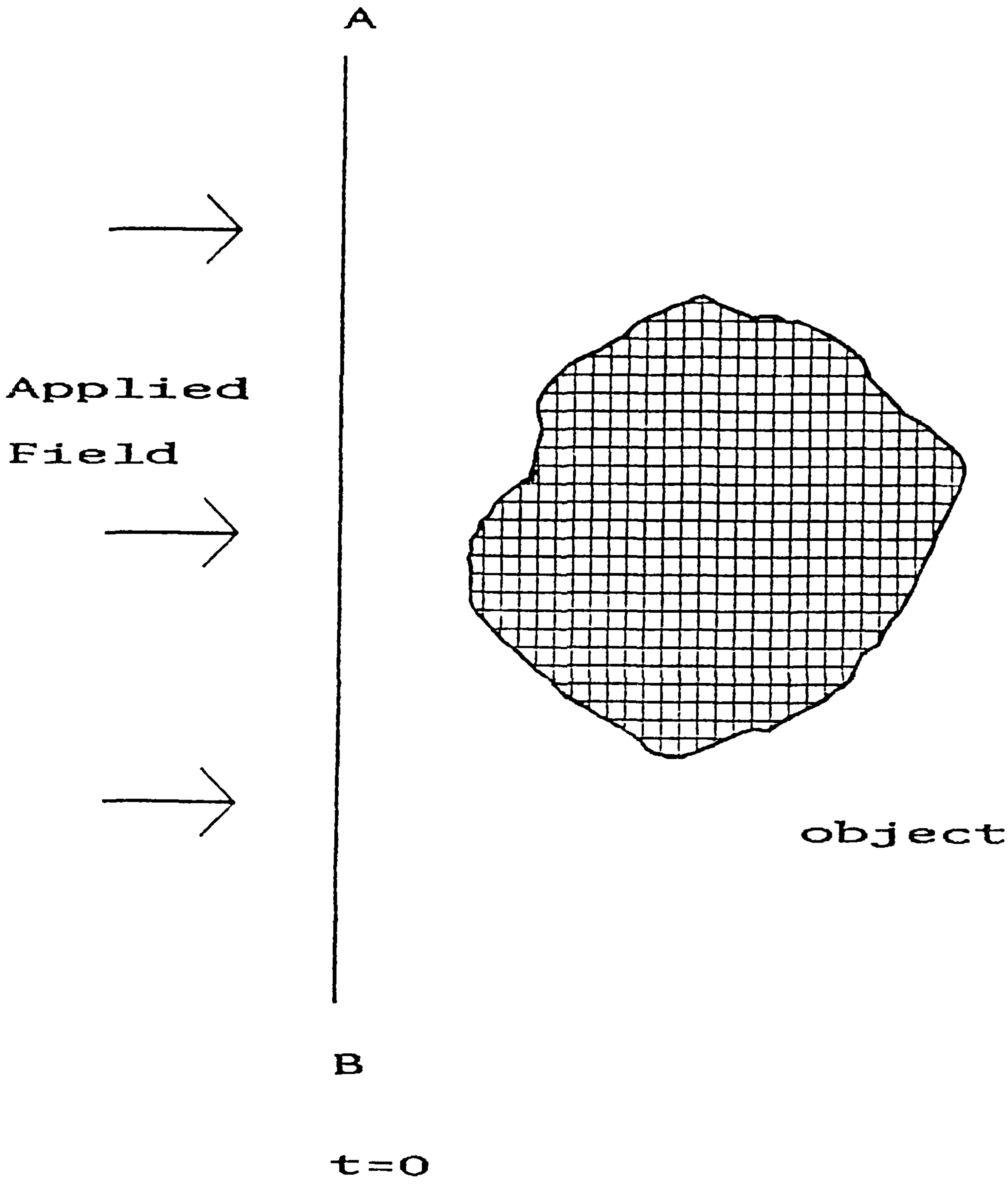

Figure 7. A general TDFDS model.

$$\nabla \wedge \boldsymbol{D} = \boldsymbol{J} + \dot{\boldsymbol{D}} \tag{2}$$

$$\nabla . \boldsymbol{D} = \rho \tag{3}$$

$$\nabla . \boldsymbol{B} = 0 \tag{4}$$

The computer uses a finite difference method to approximate these equations and time steps to follow the field as it propagates across the model and reflects at dielectric interfaces or boundaries. The matrix and differential methods mentioned briefly in Section 6.1 tend to directly compute the resultant steady state field whereas with TDFDS the EM field is seen to build up to the steady state. Thus the computer directly simulates the behavior of nature and we believe that this is one reason for the success of TDFDS with real problems. The method has been fully described (7,8).

6.3 Cells Modeled at 90 GHz

The TDFDS software is being used to predict the EM field inside various possible types of experimental cell.

The models being considered are shown in Figure 8. The cell of (a) consists of 90-GHz waveguide with the sample contained between a dielectric window and a short circuit and represents the cell being constructed at present. In model (b) a guide of larger dimensions is shown. This model represents overmoded guide, and some form of transition is needed between it and the rest of the 90-GHz system. In model (c) the side walls of the guide have been removed so that the method is essentially *in vivo* although there is still a terminating short circuit. Model (d) is (c) without a short circuit and is a true *in vivo* method. Notice that although model (b) could possibly be analyzed, at least approximately, using standard text book methods, models (c) and (d) need numerical methods since the field will diffract from the applicator and it is not completely contained by metallic boundaries. Although (c) and (d) models may appear similar it is expected that (c) model might be more sensitive particularly if the short circuit is a quarter wavelength from the applicator.

Investigations are progressing at present, and it would be premature to report any conclusions at this stage. However we are confident that if the cell being constructed, i.e., model (a), does not give sufficient accuracy, then one of the other possible designs considered could be analyzed approximately. However, a more rigorous analysis, particularly of the true *in-vivo* situation (d), is likely to be a long-term project.

7. THE BROAD-BAND SYSTEM AROUND 35 GHz

7.1 Sensitivity of the Measurements

Previous tissue measurements in our laboratory have used samples a quarter wavelength thick ($\lambda/4$); but such matching is only possible at one frequency. To observe the effect of unmatched samples a program was written for the Archimedes Computer to calculate the Voltage Standing Wave Ratio (VSWR) as a function of complex permittivity $\epsilon = \epsilon' - i\epsilon''$.

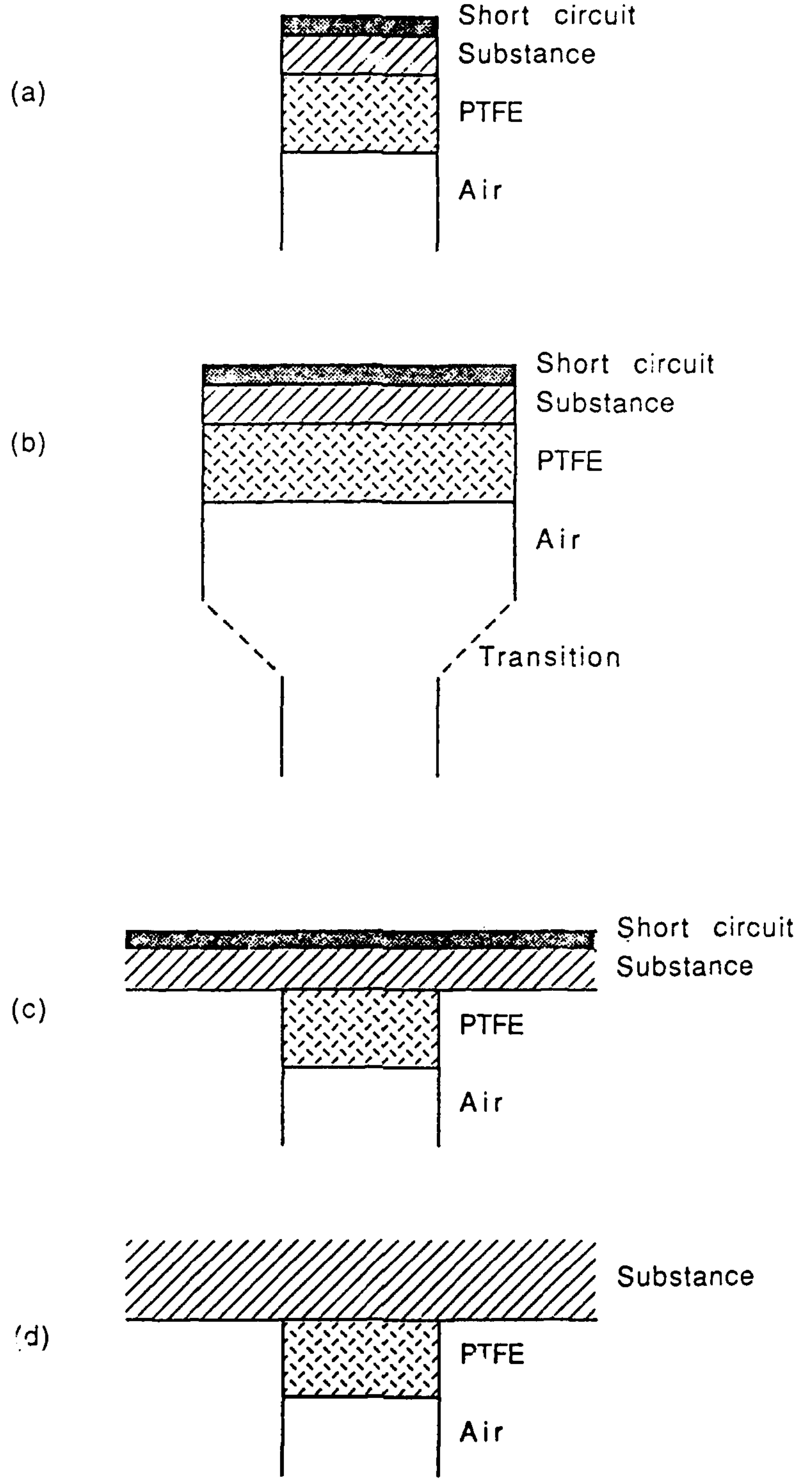

Figure 8. Various cells being modelled at 90 GHz.

The concept is shown in Figure 9(a) where a surface represents the VSWR as a function of ϵ. The results are displayed on a computer monitor, and the output for a sample of 1.5 mm is shown in Figure 9(b). It can be seen that there are multiple peaks of VSWR; the solid white line represents the permittivity at which the sample thickness is $\lambda/4$ and the white dot is the complex permittivity of water at room temperature and a frequency of 35 GHz. For maximum sensitivity the rate of change of VSWR (i.e., the slope of the surface) needs to be large with respect to ϵ' and ϵ''. It can be seen in Figure 9(b) that water is in a very insensitive region so that, as expected, such a thick sample would not yield accurate permittivity data. In Figure 9(c) the sample is 0.8 mm thick; however, the permittivity corresponding to $\lambda/4$ is still far from the water value and the method would still not be sensitive.

In Figure 9(d) the sample thickness is 0.4 mm which is close to the optimum for water. It can be seen that the solid $\lambda/4$ line is close to the water permittivity (white dot) and the sensitivity is much increased. However, as often happens, samples of lower loss (smaller ϵ'') would be more sensitive and such plots emphasize the difficulties of aqueous measurements even for optimum sample thickness.

The conclusion drawn from studying a range of such plots was that provided the sample thickness is close to $\lambda/4$ reliable data could be expected even if the sample were not perfectly matched for thickness.

To consider other sources of error in a broad-band system; provided that a broad band source of sufficient power can be obtained the main limitations are due to intrinsically narrow-band items such as isolators. Much research effort has gone into considering available equipment and particularly performance against bandwidth. As a result of this, and the computation concerning sample thickness, we believe it will be possible to operate over the full bandwidth of 26–40 GHz rather than a restricted portion of it as suggested in the original grant application.

7.2 The Experimental System

It is proposed to set up two essentially independent broad-band systems, one for liquids and the other for tissues; however, they will both be fed from one oscillator.

The source, which is a frequency locked Gunn Diode oscillator from Millitech (model GOM-28-WB-17), and its associated components is shown diagramatically in Figure 10. This source can deliver 50 mW of power over at least 80% of the band 26 to 40 GHz, with a free running stability of ±50 kHz. However, when locked to the EIP frequency counter, a stability of ±1 Hz is expected. The circuit of Figure 10 needs little explanation; however, it can be seen that a small proportion of the Gunn output is fed, via a directional coupler, to the EIP counter. This counter is linked via the IEEE Bus to an Archimedes computer so the frequency can be both monitored and changed by the computer during an experiment.

The circuit for the liquid system is shown in Figure 11. The experimental cell (sample holder) will be similar to that used in previous systems (1,2). However, a novel feature is the two directional couplers feeding into a single detector via a waveguide switch. The two couplers will monitor both the incident and reflected signals. The advantage of using one detector (and detection channel), apart from reduced cost, is that problems associated with matching detectors are avoided. The switch has been purchased

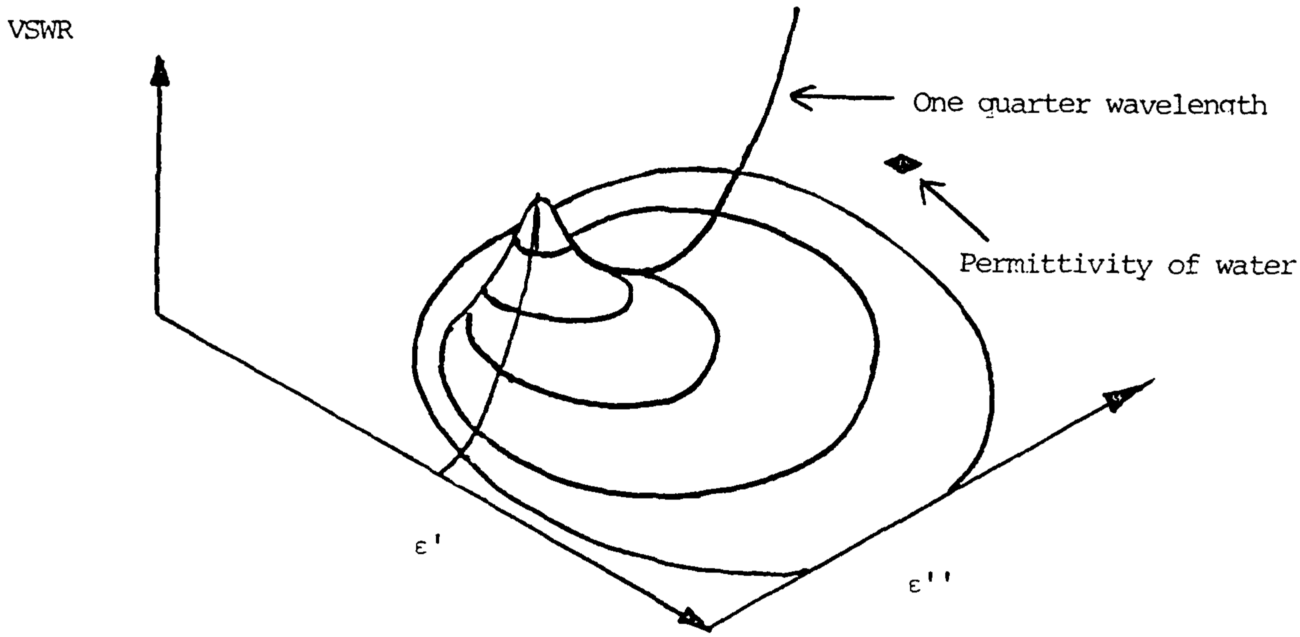

Figure 9(a). Plots of VSWR against ε' and ε" for fixed sample thickness.

Figure 9(b). A relatively thick sample.

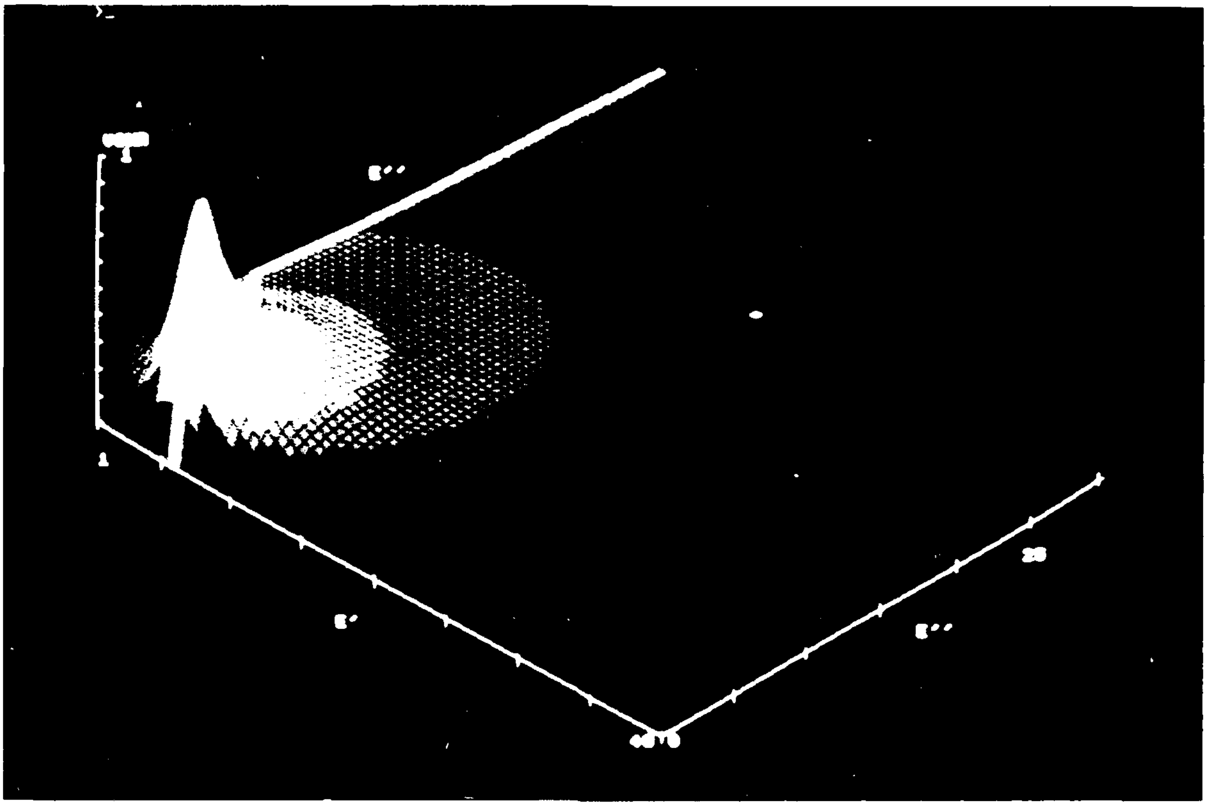

Figure 9(c). A medium thickness sample.

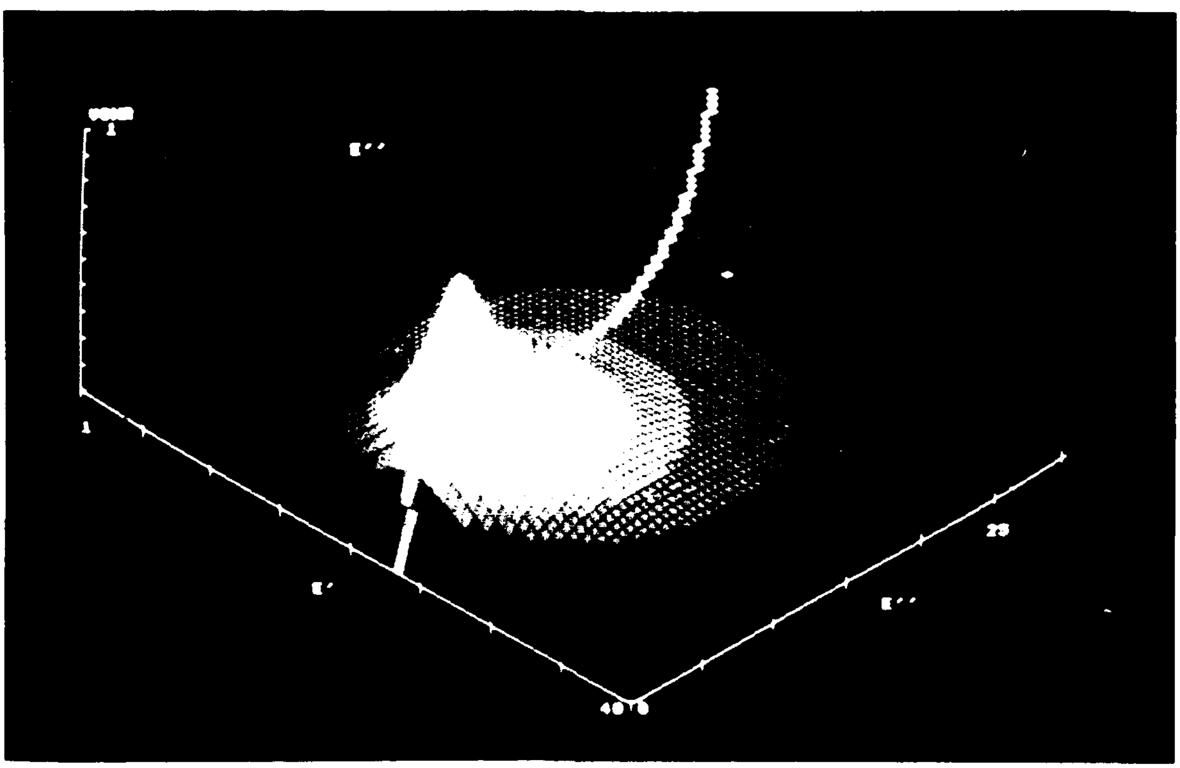

Figure 9(d). A thin and close to optimum sample.

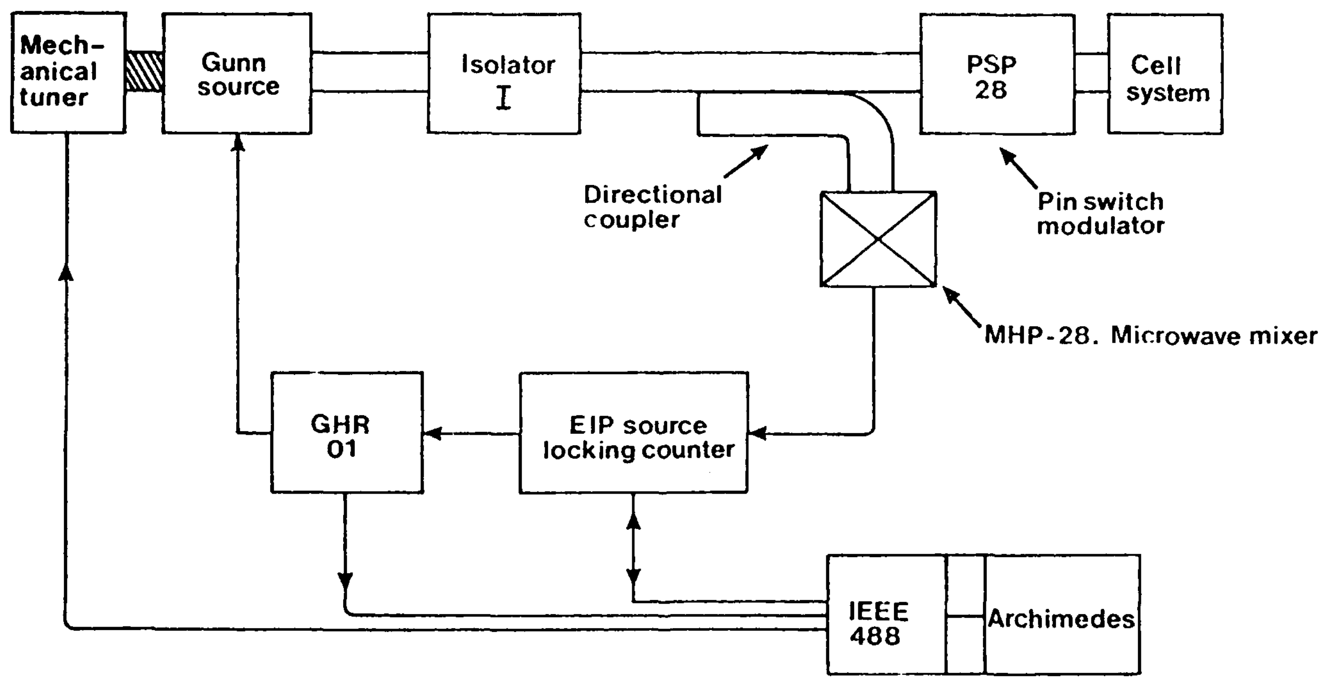

Figure 10. Twenty-six gigahertz to 40 GHz millimetric source network.

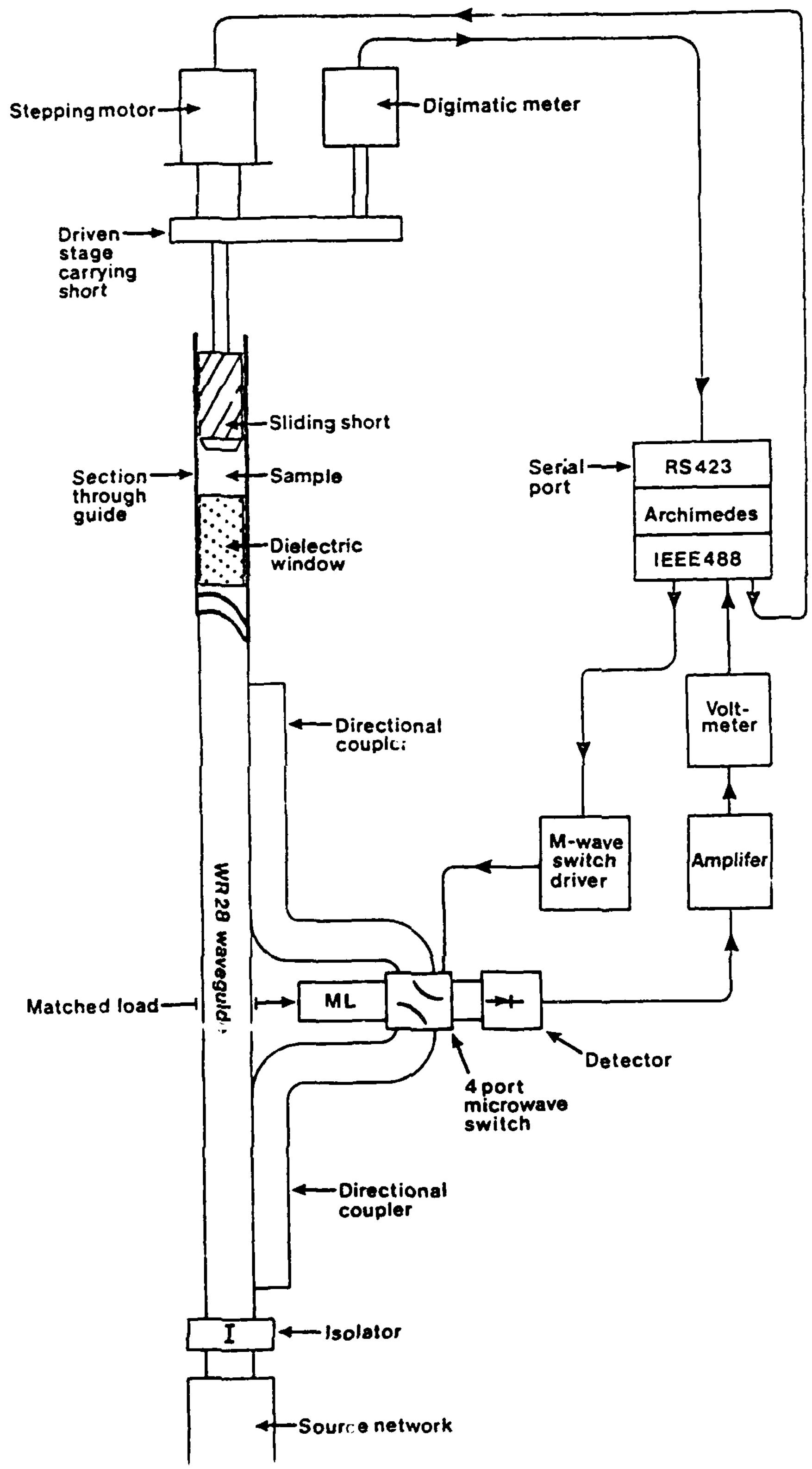

Figure 11. Twenty-six gigahertz to 40 GHz liquid-cell sample.

from Flann Microwave Limited. Although the new apparatus has not yet arrived, we have set up a preliminary system, at the fixed frequency of 35 GHz, using existing equipment. This system is shown in Figure 12; in particular, the two directional couplers can be seen although each has to feed a detector since the waveguide switch has not yet arrived.

A diagram of the system for the tissue measurements is shown in Figure 13 and follows previous practice by having a slotted line in front of the sample.

As mentioned previously, a problem with broad-band systems is the limitation of such items as isolators. However, with both the liquid and solid systems it is not proposed that a true swept frequency measurement will be made. In particular, a frequency will be set, a measurement made, and the frequency changed. Thus, each measurement although automatically controlled from the computer is independent. As a result we are confident that, provided the properties of components, such as isolators, are constant at a particular frequency no errors would be introduced if the properties varied across the frequency band. As already stated, we believe that such components are available to us.

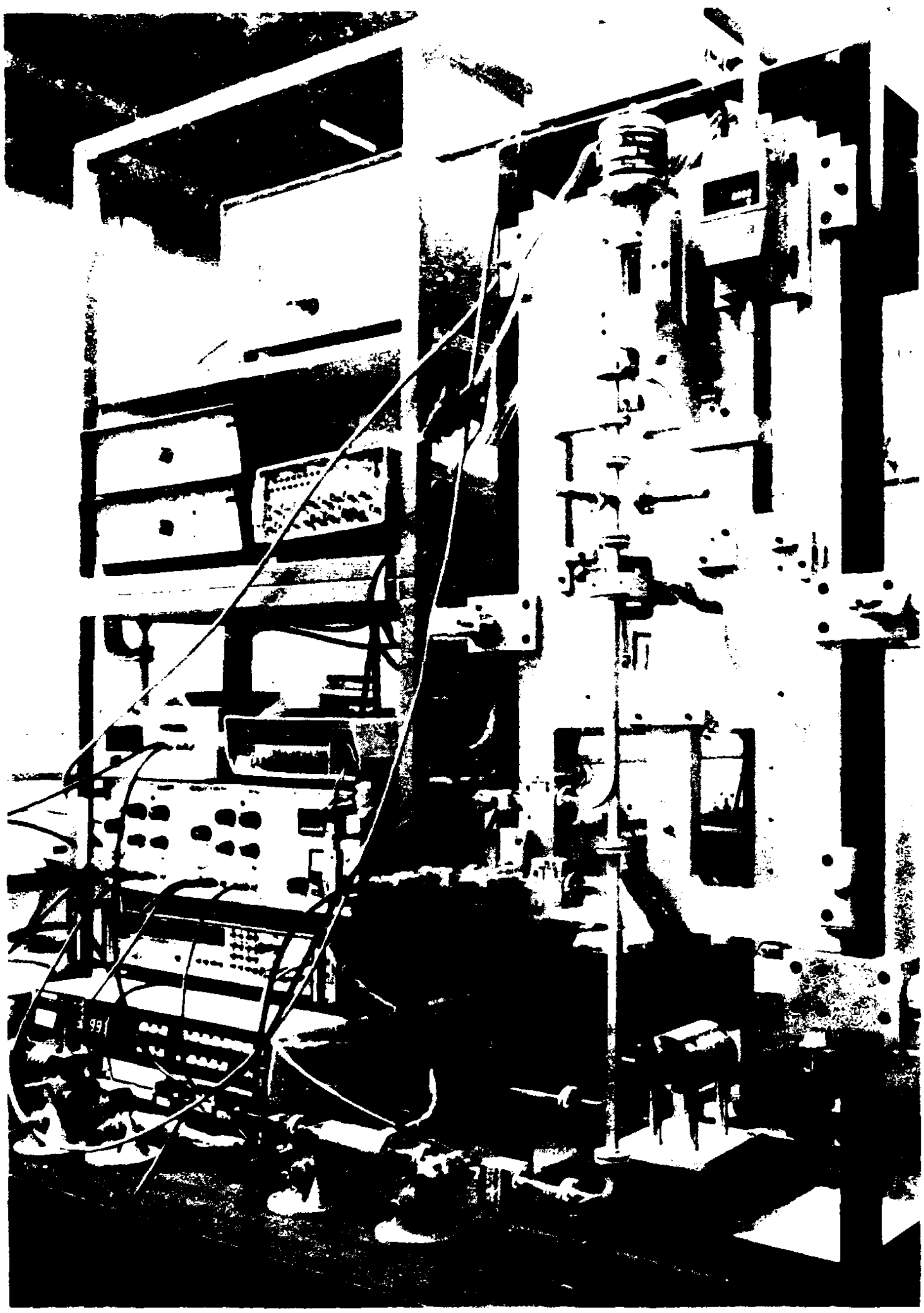

Figure 12. A preliminary realization of the liquid measuring system.

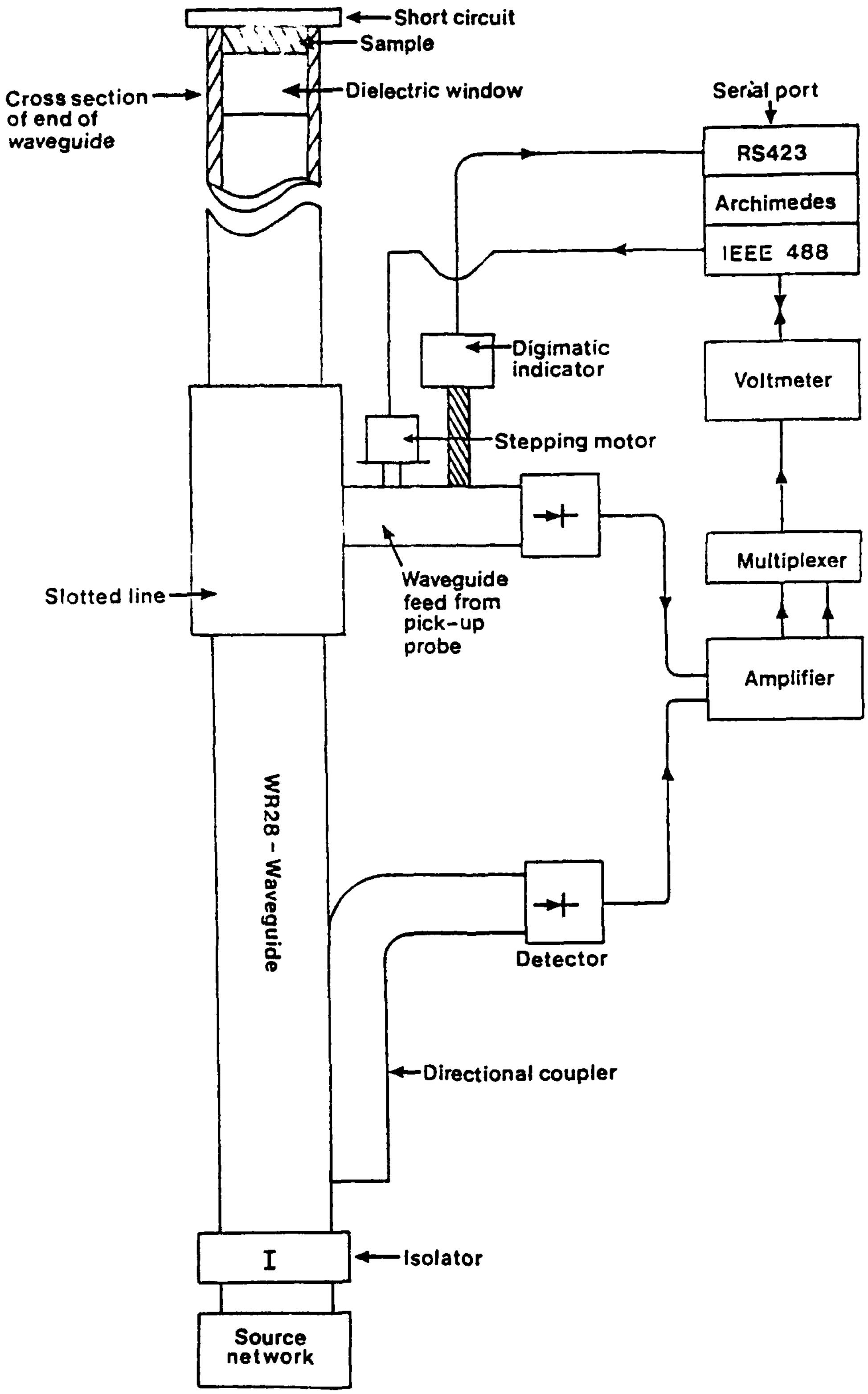

Figure 13. Twenty-six gigahertz to 40 GHz solid cell system.

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